Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Parameter estimation for optimal asteroid transfer trajectories using supervised machine learning

Haibin Shang [a,b,*], Xiaoyu Wu [a,b], Dong Qiao [a,b], Xiangyu Huang [c,d]

[a] *School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China*
[b] *Key Laboratory of Dynamics and Control of Flight Vehicle, Ministry of Education, Beijing 100081, China*
[c] *Beijing Institute of Control Engineering, Beijing 100190, China*
[d] *Science and Technology on Space Intelligent Control Laboratory, Beijing 100190, China*

A R T I C L E I N F O

Article history:
Received 23 March 2017
Received in revised form 22 March 2018
Accepted 3 June 2018
Available online xxxx

Keywords:
Asteroid mission
Optimal trajectory
Evaluation model
Gauss process regression
Compound features

A B S T R A C T

In this paper, supervised machine learning is applied to the parameter estimation for optimal asteroid transfer trajectories. Efficient models for the estimation of important trajectory parameters are developed based on the Gaussian Process Regression (GPR) technique. The essence of constructing the GPR-based model is to learn the correlation between the trajectory parameters and the selected features. The asteroid orbital elements are considered as an original feature set due to their decisive influence on transfer trajectories. Two strategies are introduced to enhance the prediction performance of GPR-based models. The first one, the grouping strategy, is able to improve the prediction accuracy by dividing the candidate asteroids into several groups. The second one is that two new compound features are constructed based on the idea of feature extraction, whose function is to provide more crucial information for the inference of transfer time. The efficiency of the proposed models is substantiated by evaluating the global optimal two-impulse transfers to inner main-belt asteroids. This paper provides a basic framework for evaluating the interplanetary trajectories by using supervised machine learning. The proposed approach can be easily extended to solve other trajectory optimization and analysis problems.

1. Introduction

Nowadays exploring asteroids has gradually attracted many scientists and engineers, and is becoming one of the hottest topics in planetary exploration. The motivations for the exploration of the asteroids are abundant. For example, asteroids are thought to be the remnants of the materials which created the Sun and the planets. Hence, they have the potential to apprize the formation, evolution and composition of Solar System [1]. In the past decades, a series of space probes have been successfully sent to some asteroid targets, such as NEAR [2], Hayabusa [3], and Chang'e 2 [4]. Besides, more exploration programs including capture [5], impact [6] and sample return [7] are ongoing.

It is estimated that millions of asteroids exist in the Solar System. To date, more than seven hundred thousand asteroids have been identified, and continually, thousands more new asteroids are discovered for each year [8]. Due to the huge number and various types of asteroids, the target selection is an important issue for the asteroid mission design. Generally, two main aspects should be considered: scientific interest and technical feasibility. From the viewpoint of the technical feasibility, it is crucial to determine the optimal trajectories to reach potential candidate asteroids for the purpose of the fact that the fuel consumption, launch energy, and/or mission duration are minimized [9]. Optimal trajectories design involves the computation of an open-loop solution for an optimal control problem. In previous researches, numerical optimization methods are the most general used techniques for solving the problem [10–15]. Practically, these various methods involve the type of iteration with a finite set of unknowns, which can maximize or minimize some quantities of importance. In terms of the asteroid target selection problem, numerical optimization methods are efficient when the number of candidate asteroids is small. Moreover, it is expected to include more potential candidate asteroids in the determination of the most feasible targets. When the number of candidate asteroids increases to a huge quantity, the computational effort of numerical optimization methods may become unacceptable due to the process of iteration, thus leading that a computationally efficient technique is highly desirable.

In a same mission scenario, each asteroid corresponds to a certain optimal transfer trajectory because that the asteroids have

* Corresponding author at: School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China.
E-mail addresses: shanghb@bit.edu.cn (H. Shang), wuxiaoyubit@yahoo.com (X. Wu), qiaodong@bit.edu.cn (D. Qiao), huangxyhit@sina.com (X. Huang).

https://doi.org/10.1016/j.ast.2018.06.002
1270-9638/

different orbital and physical parameters. It reveals that a correlation may exist between the asteroid's parameters and the optimal trajectory (some quantities of importance). If the correlation is found, the parameters of an optimal transfer trajectory can be effectively estimated. In fact, the exploration for the correlation among variables can be considered as a regression problem from the viewpoint of mathematical statistics, which mainly focuses on the prediction of the continuous dependent variables when the independent variables are given. Regarding it as a supervised problem of machine learning, many popular techniques have been developed, such as support vector machines [17], neural networks [18], and Gaussian Process methods [19]. In this paper, Gaussian Process Regression (GPR) is used to analyze the optimal asteroid transfer trajectories due to its flexible and simple implementation in practice, as well as the good predictive capability.

GPR technique has been widely applied in many areas [20–22]. Besides, one more popular application refers to the robot arm inverse dynamics problem, in which GPR method offers a fast and accurate estimation of unknown nonlinearities in inverse dynamics model, thus allowing the robust and real-time tracking control of complex robots [19,23]. Our previous research shows that GPR is a computational efficient algorithm to estimate the near-global optimal ΔV required for asteroid rendezvous missions. This work is a continuation and extension of our previous research, and its aim is twofold. The first one is to improve the prediction accuracy of the GPR-based model which was proposed previously. The grouping prediction strategy is introduced to achieve this purpose. This strategy is based on the similarity between data points, which is a basic assumption in supervised learning. Through dividing the asteroids into several groups, it is convenient to build more accurate GPR-based prediction models for some important trajectory parameters (e.g. total ΔV and launch energy C_3). The second one aims to improve the GPR-based model to predict the transfer time more efficiently, which cannot be implemented by our previous model. Using the idea of features extraction, two new compound features closely relevant to transfer time are discovered and constructed, thus leading that the GPR-based model can extract more useful information from the new feature set, and improve the prediction performance for transfer time.

The structure of the paper is organized as follows. In Section 2 the two-impulse transfer models for asteroid missions are built, and the optimization method to generate the global optimal transfer trajectory is presented. In Section 3 the GPR technique is discussed, including the generation of training as well as test samples, the selection of covariance function, and the details of the model training algorithm. Section 4 presents two strategies to enhance the prediction performance of the GPR-based model, and then the developed GPR-based models are applied to evaluate the optimal trajectories to inner main-belt asteroids. Section 5 concludes this paper.

2. Global optimal two-impulse trajectory

The classical two-impulse transfer plays an important role in a preliminary trajectory design for a space mission. In an asteroid rendezvous mission, the optimal two-impulse transfer is usually employed as the basis scenario to evaluate the mission cost because of its simple implementation [24]. In this paper, the ephemeris-free optimal two-impulse transfer between the Earth and an asteroid is discussed. The resulting transfer can be considered as the global optimum. It is assumed that the spacecraft is initially placed in a circular parking orbit around the Earth with an altitude of H. After the process that an orbital maneuver (denoted as ΔV_1) is performed, the spacecraft leaves the Earth's gravitational pull, enters a hyperbolic trajectory, and then flies towards the target asteroid. When it arrives at the target, the second orbital maneuver ΔV_2 is performed to ensure that the spacecraft rendezvous successfully, as shown in Fig. 1. Generally, the influence of asteroid's gravity on the trajectory is neglected due to its small mass. During the transfer process, it can be considered that the spacecraft motion is governed by the gravitational fields of Earth and the Sun. Moreover, the patched-conic approximation is used to further simplify the trajectory calculation. Under these above assumptions, the decision variables for trajectory optimization problem can be expressed as

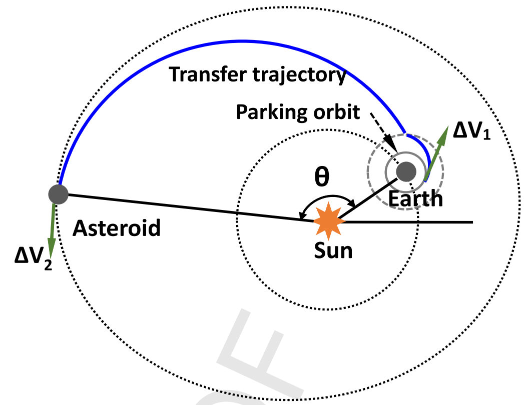

Fig. 1. The illustration of a two-impulse transfer trajectory from the Earth to the target asteroid.

$$\boldsymbol{\chi} = [M_E, M_A, t_{EA}] \tag{1}$$

where M_E and M_A in Fig. 1 and Eq. (1) denote the mean anomalies of the Earth at departure and the asteroid at arrival, respectively, and t_{EA} denotes the total transfer time.

The optimal trajectory which aims at minimizing the total velocity increment can be found through

$$J(\boldsymbol{\chi}) = \Delta V_{EA} = \Delta V_1 + \Delta V_2 \tag{2}$$

These two orbital maneuvers are calculated as follows

$$\begin{aligned} \Delta V_1 &= \sqrt{\|\boldsymbol{v}_1 - \boldsymbol{v}_E\|^2 + \frac{2\mu_E}{r_E + h}} - \sqrt{\frac{\mu_E}{r_E + h}} \\ \Delta V_2 &= \|\boldsymbol{v}_2 - \boldsymbol{v}_A\| \end{aligned} \tag{3}$$

where r_E denotes the Earth's mean radius, and μ_E denotes the gravitational constant of the Earth; $\boldsymbol{v}_1$ and $\boldsymbol{v}_E$ denote the spacecraft's and the Earth's heliocentric velocity vectors at the Earth departure time, respectively. Similarly, $\boldsymbol{v}_2$ and $\boldsymbol{v}_A$ are the spacecraft's and the asteroid's heliocentric velocity vectors at the asteroid arrival time. Given the decision variables $\boldsymbol{\chi}$, $\boldsymbol{v}_1$ and $\boldsymbol{v}_2$ can be obtained by solving the single-Lambert's problem which limits that the transfer phase angle Θ is less than 360 degree and leads that the transfer time is an acceptable value for missions.

Various methods can be used to solve the unconstrained optimization problem, such as Newton's method [25], Nelder–Mead method [26], and population-based method [27,28]. Generally, the optimal solution can be obtained by these various methods. However, the result may be solved as a local solution because that many locally optimum points exist in the problem. Fig. 2 shows the ΔV_{EA} contour slices of two-impulse transfer to an example target 323 Brucia. It can be seen that several extreme points may exist. Table 1 lists three locally optimal solutions, indicating the potential mission opportunities of 323 Brucia. In practice, the near-global optimal solution is desired to generate the high quality samples for machine learning algorithm. In this paper, the Differential

Please cite this article in press as: H. Shang et al., Parameter estimation for optimal asteroid transfer trajectories using supervised machine learning, Aerosp. Sci. Technol. (2018), https://doi.org/10.1016/j.ast.2018.06.002